EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 77 NUMBER 31

JULY 30, 1996

PAGES 289–304

Multi-Use Seismic Stations Offer Strong Deterrent to Clandestine Nuclear Weapons Testing

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As the United States and other nations push for the signing of a Comprehensive Test Ban Treaty, representatives are meeting in Geneva this year to develop an International Seismic Monitoring System to verify compliance with the treaty's restrictions. In addition to the official monitoring system, regional networks developed for earthquake studies and basic research can provide a strong deterrent against clandestine testing. The recent release of information by the U.S. Department of Energy (DoE) on previously unannounced nuclear tests provides an opportunity to assess the ability of multi-use seismic networks to help monitor nuclear testing across the globe.

Here we look at the extent to which the formerly unannounced tests were recorded and identified on the basis of publicly available seismographic data recorded by five seismic networks. The data were recorded by networks in southern Nevada and northern California at stations less than 1500 km from the Nevada Test Site (NTS), and two networks in the former Soviet Union at stations farther than 1500 km from the NTS.

With the exception of some of the Soviet stations, none of the networks analyzed were charged with monitoring the NTS. These networks, however, detected 85% of all unannounced tests performed underground at the NTS, and 73% were listed in open seismic catalogues prior to the DoE announcement. Soviet stations, at epicentral distances as great as 10,000 km from the test site, identified all unannounced tests with an estimated magnitude of 4 or larger. U.S. networks, located at regional distances, detected 89% of all tests since 1983, and these tests had seismic magnitudes between 1.4 and 4.5.

While this study should not be regarded as a comprehensive evaluation of the monitoring capability of seismic stations, it does demonstrate the increasing capability of multi-use seismic stations and networks to detect and identify small seismic events. This capability will be useful for monitoring once an international Comprehensive Test Ban Treaty is signed.

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Seismic Event Detection at the Nevada Test Site

Since December 1993, the DoE has released information on 204 unannounced nuclear tests performed underground at the Nevada Test Site (NTS). The information on each test included its date and time, the test area, the depth of burial, and a yield range.

The NTS was established in 1951 and is located in the Basin and Range province, a region that is marked by high seismicity with earthquakes at shallow depths (Figure 1). In this tectonic setting, the most difficult task of identifying a nuclear test is to discriminate the event against regional earthquakes. Large seismic events at the NTS are generally recorded by enough seismic stations and with a sufficient signal-to-noise ratio to allow the identification of the event on the basis of distinct signal characteristics. Furthermore, relatively few earthquakes occur each year within the general area of the NTS with magnitudes larger than two or three (Figure 1) [*Gomberg*, 1991; *Gawthrop and Carr*, 1988].

DoE's policy is to only report the yield of announced tests as either less than 20 kT or 20–150 kT [*U.S. Congress*, 1989]. With a few exceptions, two tests in 1970 and 1973, all of the previously unannounced tests were reported to have yields below 20 kT and may have been quite small.

The detection and identification of small seismic events at the NTS can be difficult. Small events are likely to be recorded by only a few stations, and the recordings often show poor signal-to-noise ratios, making such events difficult to detect and identify. Unfortunately, at the same time, several hundred earthquakes with magnitudes smaller than two are detected at the NTS each year (Figure 1).

Several facts can help in identifying nuclear tests at the NTS. First, the geographic boundaries of the relatively small areas used for testing are well known. Second, relatively few earthquakes with magnitudes above 2 or 3 occur within the NTS region despite the relatively high seismicity. Finally, most nuclear tests are performed at depths less than 600 m while most earthquakes in this region occur at depths greater than 5–8 km. Consequently, in the routine analysis of seismic data, regional and teleseismic networks generally designate a detected seismic event as a nuclear test at the NTS if the event can be conclusively located at shallow depth within the relatively small regions used for testing.

NTS Explosions Recorded at Regional Distances

The ability of regional networks to detect small, unannounced tests at the NTS is demonstrated using data from the following three networks established to monitor regional tectonic processes along the San Andreas Fault System and across the Basin and Range province: the Southern California Seismographic Network (SCSN), run jointly by the California Institute of Technology and the United States Geological Survey; the Southern Great Basin Seismographic Network (SGBSN), operated by the United States Geological Survey prior to 1992; and the Western Great Basin Seismographic Network (WGBSN), operated by the University of Nevada at Reno.

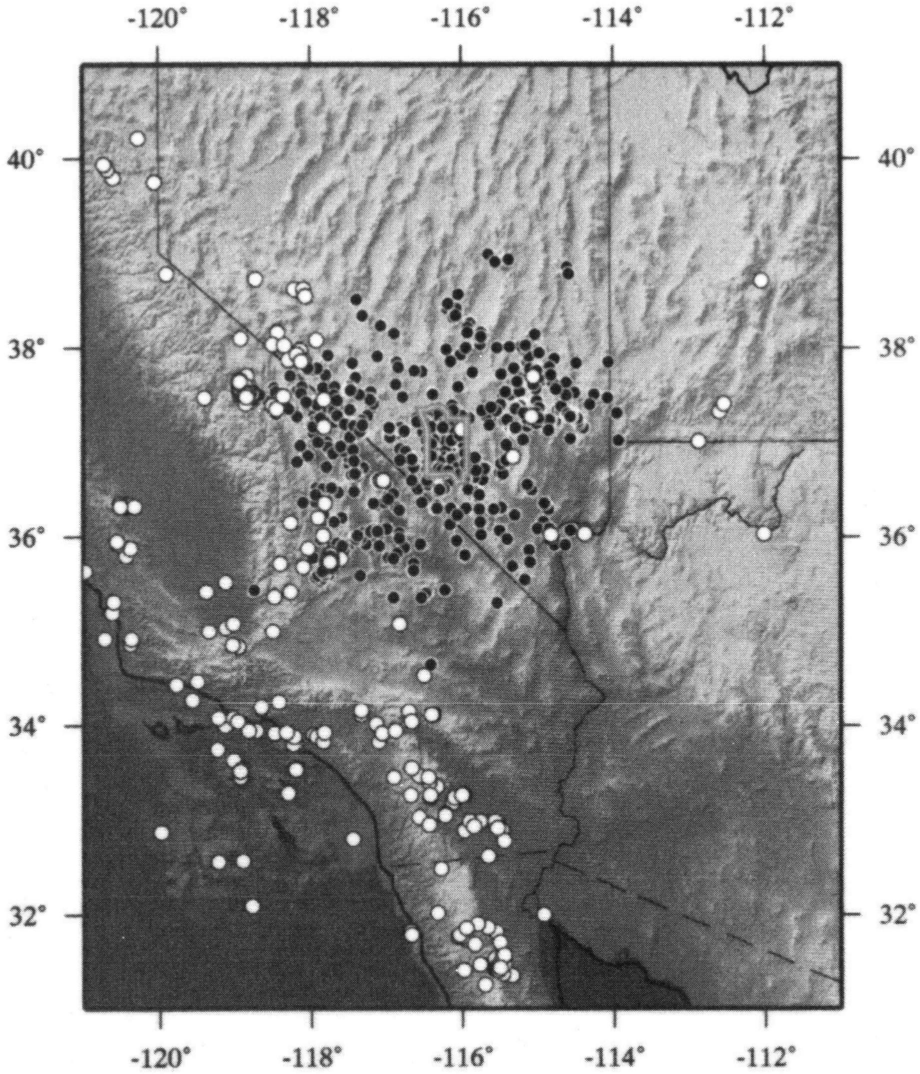

Fig. 1. Earthquake epicenter locations for the year 1982 for a region centered around the Nevada Test Site (in red). The Southern Great Basin Seismographic Network recorded 945 events (black dots) in its bulletin. Of these, 331 events had local magnitudes (M_L) between 1 and 2; 43 events had M_L between 2 and 3; and two events had M_L above 3. Events listed in the National Earthquake Information Center Bulletin *(white dots) include one event located in the northeast part of the test site. This event was interpreted as an earthquake with magnitude (m_b) 3.2 and occurred on December 12, 1982, at a depth of 15 km. Original color image appears at the back of this volume.*

As mentioned earlier, none of these networks had the specific task of monitoring the NTS for testing activity, nor were they designed for that purpose. During the first decade of unannounced nuclear testing at the NTS, the SCSN was operating four single-component stations along the California/Nevada border with the closest station approximately 200 km from the test site. By 1986, the SCSN had increased its station density in this region to 12 stations. The SGBSN and WGBSN, initially installed in the late 1970s and 1960s, respectively, reached a station density of approximately 100 mostly single-component high-frequency seismic stations deployed within a radius of 300 km of the test site in the early 1980s.

Over the three decades examined, the regional networks included in this study used two distinctly different procedures to detect and catalog seismic events. The SCSN monitored all seismic activity using continuous analog recordings. Analysts routinely examined the SCSN recordings to detect, identify and catalog seismic events of interest. The SGBSN and the WGBSN relied mostly on automatic event detection. To detect and declare a preliminary event, these networks required three or more stations to automatically trigger the recording of the event, which analysts would then identify and catalog.

Prior to the DoE's disclosure, U.S. regional networks independently detected 73% (148) of all previously unannounced nuclear tests (Figure 2). These tests were listed at the time of their occurrence in the open bulletins of the networks. Since 1983, when unannounced nuclear testing resumed after a 3-year period during which all tests were announced, regional networks independently detected 89% (16 of 18) of all unannounced tests.

The smallest signals detected were those from a test on December 9, 1988, with a local magnitude of 1.6, and one test on August 14, 1985, with a local magnitude of 1.4. Although these tests were extremely small, they were recorded by enough instruments to identify them within the boundaries of the approximately 500 km^2 NTS Yucca Flat test area. The location estimate for the 1988 test was within 1.3 km of the drillhole and 300 m of the true burial depth.

After the DoE disclosure of the test detonation times, the total number of detected unannounced tests reached 85% when the reexamination of the continuously recorded seismic data at the SCSN revealed evidence of 25 additional tests that were not listed in the bulletins of the networks at the time they occurred (Figure 2). Of these 25 tests, 21 had been performed in the 1960s and four in the 1970s. While the smallest tests listed in the bulletins during this time period had magnitudes between 3.0 and 3.5, the smallest tests detected after the DoE announcement had magnitudes of about 2.2.

Surprisingly, some of these tests were estimated to have magnitudes above 2.6, the threshold magnitude for the SCSN to discriminate events at the NTS. These relatively large tests may have been recorded by SCSN stations, but not listed in their bulletins due to the strictly scientific focus of the network. The detection of nuclear tests was not considered important during such times of frequent testing, and therefore nuclear tests were often excluded from the earthquake bulletins.

No evidence was found in the archived SCSN records to confirm about 15% of the previously unannounced tests at the NTS. Most of the undetected tests were conducted during the 1960s and 1970s. Only two tests conducted since the early 1980s remain seismically undetected: one on September 29, 1983, and another on October 30, 1985 (Figure 2). When these tests were detonated, the SGBSN, with a detection threshold of less than magnitude 1 for events located on the test site, had only one or two stations deployed near the test area. Since the tests were not detected, it is likely that they were extremely small, with magnitudes below the SGBSN detection threshold, and that their yields were equivalent to no more than a few tens of tons [*Richards and Zavales*, 1996; *Murphy*, 1981].

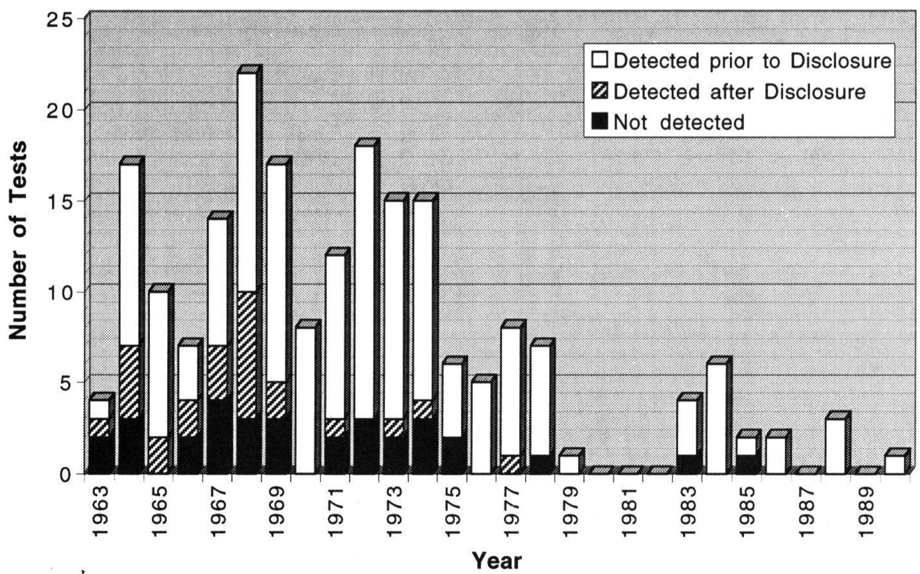

Fig. 2. Histogram of 204 previously unannounced tests performed underground at the Nevada Test Site. Prior to the DoE's announcement of the tests, 73% (149 of 204) were detected and are listed in open seismological bulletins. The rate of detection increased to 89% (16 of 18) for tests conducted since 1983. After the DoE announcement, the number of all tests seismically detected from 1963 onward increased to 85% (173 of 204).

Overall, 31 tests could not be confirmed in this study. This number may decrease as additional data become available. However, some U.S. nuclear tests had zero yields, which cannot be detected seismically. This may account for at least a few of the unannounced tests. Zero yield tests, however, are not of great concern to monitoring efforts aimed at uncovering a clandestine nuclear weapons design program.

NTS Explosions Recorded at Teleseismic Distances

At teleseismic distances (larger than 1500 km), monitoring at the NTS is strongly dependent on ray path; and at distances several thousand kilometers from the NTS test site, the ability of stations and networks to detect small tests varies significantly. The following analysis is based on data from two networks in the former Soviet Union (FSU) that were operated by the Complex Seismological Expedition (CSE) of the Russian Academy of Sciences' Institute of the Physics of the Earth and its Institute of the Dynamics of the Geosphere (IDG).

These networks were initially installed to monitor global and regional seismicity, to provide high-quality seismic data for research on local microseismic noise conditions, and to monitor nuclear explosions. Between 1961 and 1990, IDG and CSE operated more than 160 seismic stations and arrays throughout the FSU, many of which were equipped with three-component, broadband channels as well as narrowband vertical channels.

Over several decades of monitoring, some IDG and CSE stations showed high sensitivity to events at the NTS. For those stations, the epicentral distances to the NTS vary from about 5000 km for station Iul'tin in eastern Russia to about 10,000 km for stations Borovoye and Zerenda in Northern Kazakhstan (Figure 3). Despite the great distance from the NTS, Northern Kazakhstan is known to be a superior location for monitoring the test site because of low seismic attenuation for ray paths from the NTS and the very low microseismic noise levels [*Richards et al.*, 1992; *Adushkin and An*, 1990].

The capability of station Borovoye in Northern Kazakhstan to monitor the NTS is illustrated in Figure 3 (inset), in which the unfiltered seismograms of two unannounced tests detonated at the NTS in the early 1970s are shown. One test on October 14, 1971, had an explosive yield of less than 20 kT. Another on June 21, 1973, was one of the two unannounced tests with a yield above 20 kT. In spite of their low yields, 36% of all of the unannounced tests at the NTS were detected and identified by stations within the FSU. Soviet stations have detected 61% of all undeclared tests conducted at NTS since 1983. The majority of the tests were recorded by stations in Northern Kazakhstan.

While the identification of detected events on the basis of location and signal characteristics led to the misidentification of only one test, magnitude estimates derived from different stations within the networks vary significantly. No simple relationship could be observed for body wave magnitude values (m_b) obtained from IDG/CSE stations and local magnitude values (M_L) obtained from U.S. regional networks. Magnitude estimates derived by the IDG deviate from those of the SCSN by values of -0.2 to +0.7. Magnitudes derived from stations in Northern Kazakhstan vary by up to 0.7 units.

To allow a direct comparison between events detected at teleseismic and regional distances, we assigned magnitude values derived by the SCSN to all tests detected by IDG and CSE. Three tests with magnitudes smaller than M_L 3.5 were detected by Soviet

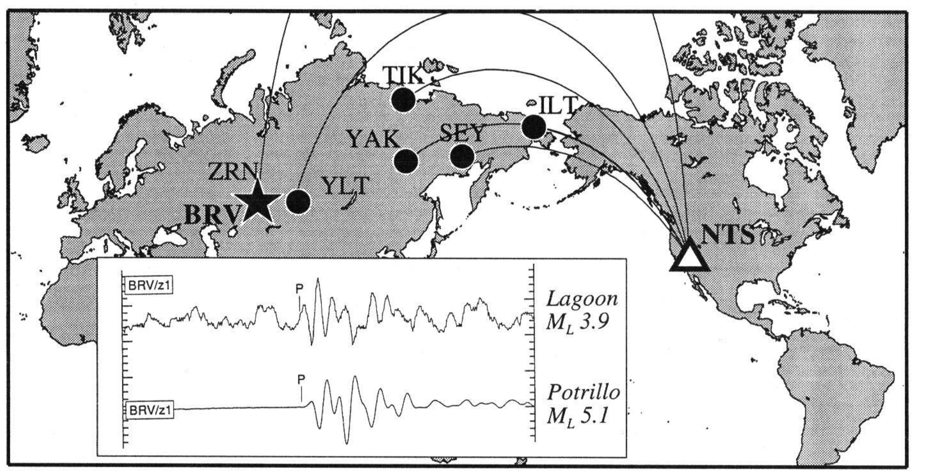

Fig. 3. Location map of teleseismic stations most sensitive to events at the Nevada Test Site. Solid circles denote teleseismic stations: ILT, Iul'tin; SEY, Seymchan; TIK, Tiksi; YAK, Yakutsk; and YLT, Yel'tsovka; star denotes Borovoye (BRV) and Zerenda (ZRN) in Northern Kazakhstan; open triangle denotes Nevada Test Site (NTS). Minor arcs indicate shortest distances between the NTS and seismic stations. Distances to the Nevada Test Site increase from about 5,000 km for station Iul'tin in eastern Russia to about 10,000 km for stations Borovoye and Zerenda in Northern Kazakhstan. (Inset) Two previously unannounced tests as recorded by station Borovoye in Northern Kazakhstan with magnitude estimates (M_L) as determined by the Southern California Seismographic Network.

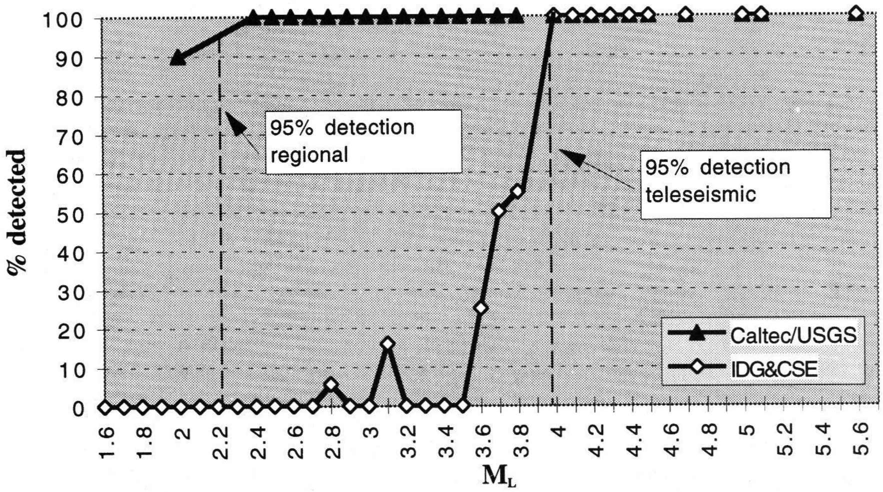

Fig. 4. Capability of former Soviet Union (FSU) stations to detect nuclear tests at the Nevada Test Site. Magnitude values (M_L) were taken from Southern California Seismographic Network catalogues, and assigned to tests detected by the Russian Academy of Sciences' Institute of the Dynamics of the Geosphere and Complex Seismological Expedition. All tests with M_L 4.0 or greater were detected and identified as nuclear tests by FSU stations.

stations (Figure 4). With 95% probability, these stations detected unannounced nuclear tests at the NTS with magnitudes between M_L 3.9 and 4.0. This finding confirms threshold magnitudes derived from announced tests for station Borovoye [*Adushkin and An*, 1993]. All unannounced tests with M_L 4.0 or greater were independently detected and identified as nuclear tests by stations within the former Soviet Union.

Conclusions and Implications for Nuclear Monitoring

The analysis of the unannounced tests clearly demonstrates the value of multi-use seismic stations as a strong deterrent to clandestine nuclear weapons testing. Any nation attempting a secret nuclear weapons test would have to take into account not only the formal treaty monitoring network, but also the increasing number of multi-use seismographic networks that are being deployed around the world.

At teleseismic distances, the capabilities of these networks might be as low as magnitude 4 or below, as indicated by the capability of the Russian networks to monitor nuclear explosions at the Nevada Test Site. A magnitude 4 seismic event corresponds roughly to a 1-kiloton nuclear weapon test. If stations exist within regional distances, the capability might be further reduced below magnitude 2, as indicated by the capability of the western U.S. networks to detect events at the Nevada Test Site. A detection threshold below magnitude 2 would preclude the likelihood of a tamped explosion of even a few tons going undetected.

No matter what system is developed for the routine monitoring of a CTBT, additional resources will exist for most areas of the world that can contribute to the monitoring task. As the United States and other nations negotiate a Comprehensive Test Ban Treaty, the strong deterrence value of existing multiple-use seismographic networks should be recognized and provisions should be incorporated within the treaty to encourage open access to the data from such networks.

Acknowledgments

We thank Joan Gomberg, Stephen Harmsen, Diane dePolo, and Martha Savage of the University of Nevada, Reno, for generously providing technical information on the SGBSN and the WGBSN, and for checking seismic bulletins for test information. This work was performed at the request of the United States Congressional Office of Technology Assessment.

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Observations Suggest Earth's Inner Core Spins Faster Than the Earth Itself

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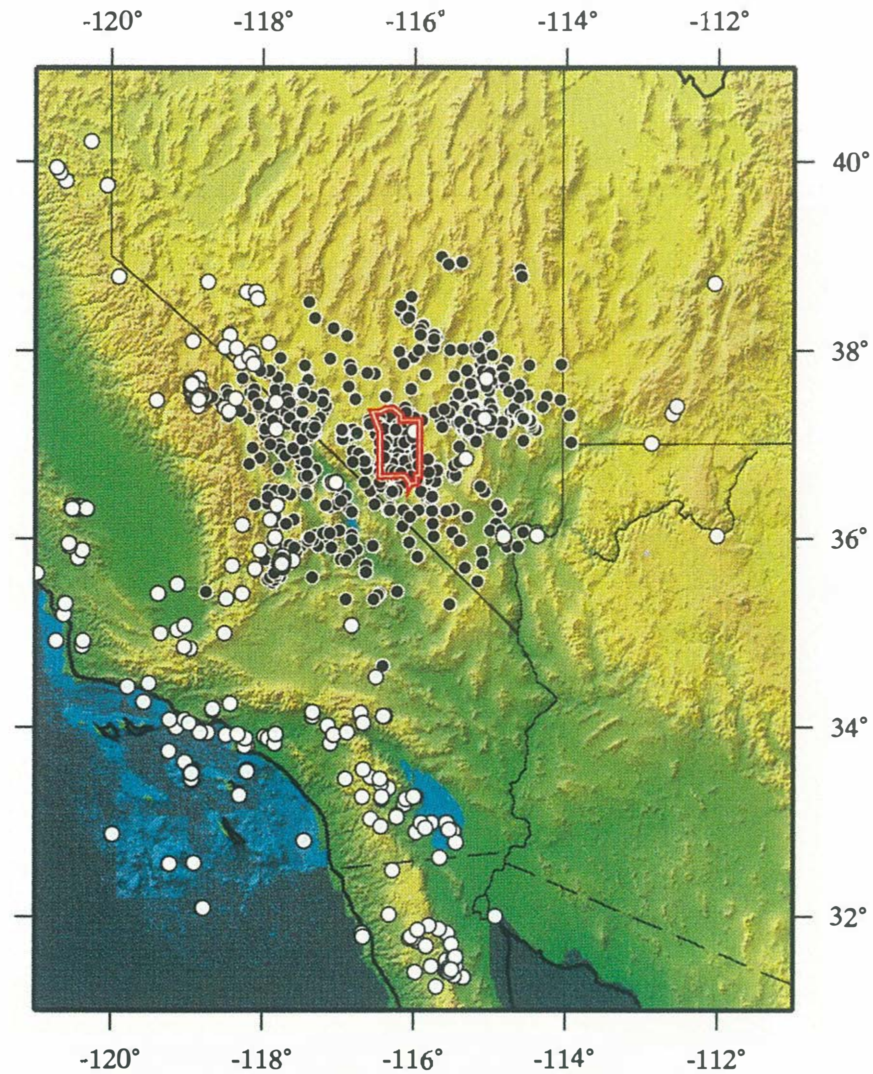
The inner core and the rest of the Earth are perpetually racing one another, and it seems the inner core is winning by a stunning distance. This proposition, once wholly abstract and theoretical, now has firm grounding in quantifiable observation.

That the solid inner core of Earth should rotate—and faster than its surroundings—has been suspected, modeled, and postulated for about a decade, but never verified. Now two seismologists from the Lamont-Doherty Earth Observatory, Xiaodong Song and Paul Richards, have announced that seismological records provide the evidence geophysicists need to confirm that the inner core is spinning.

According to Song and Richards, the Earth's innermost core rotates in the same direction as the rest of the planet, but slightly faster. The researchers have calculated that in one day the inner core spins about two-thirds of a second faster than its surroundings. Therefore, in a year, a given point on the surface of the core turns almost 19 km further than a point on the surface of the crust. Such movement is about 100,000 times faster than the drift of the continents, and it means that the core essentially laps the Earth by a complete revolution every 400 years. In the past century of seismological measurements, the core has gained about a quarter turn on the whole planet, Song and Richards found.



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